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TECHNICAL REPORT

An Optical Fiber Infrasound Sensor

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June 2006

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13. ABSTRACT (Maximum 200 words)

We have designed a new type of infrasonic sensor using optical fibers as distributed sensing elements. The design addresses the limitations of the standard pipe filters currently used to average wind-generated, turbulent pressure fluctuations. In addition to maximizing the signal-to-noise ratio, the ysstem has the capability to help estimate signal azimuth and phase velocity. The principal advantage of the Optical Fiber Infrasound Sensor (OFIS) over the standard pip filter/microbaragraph combination is that it meaasures the intetrated pressure variations along its length, not an acoustical sum of the pressure at many points, as is the case for the pipe filter.

The OFIS can be made arbitrarily long and deployed in an arbitrary geometry. As its output is the integral of the pressure field along its length, the OFIS is inherently sensitive to signal directivity and can be deployed as a directional array element. We have assembled a prototype optical fiber infrasound sensor, have performed laboratory evaluations, and have run comparisons of the new sensor with more traditional sensors in the field.

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CONVERSION TABLE

Conversion Factors for U.S. Customary to metric (SI) units of measurement.

MULTIPLY ⟶ BY ⟶ TO GET
TO GET ⟵ BY ⟵ DIVIDE

angstrom	1.000 000 x E -10	meters (m)
atmosphere (normal)	1.013 25 x E +2	kilo pascal (kPa)
bar	1.000 000 x E +2	kilo pascal (kPa)
barn	1.000 000 x E -28	meter^2 (m^2)
British thermal unit (thermochemical)	1.054 350 x E +3	joule (J)
calorie (thermochemical)	4.184 000	joule (J)
cal (thermochemical/cm^2)	4.184 000 x E -2	mega joule/m^2 (MJ/m^2)
curie	3.700 000 x E +1	*giga bacquerel (GBq)
degree (angle)	1.745 329 x E -2	radian (rad)
degree Fahrenheit	$t_K = (t^of + 459.67)/1.8$	degree kelvin (K)
electron volt	1.602 19 x E -19	joule (J)
erg	1.000 000 x E -7	joule (J)
erg/second	1.000 000 x E -7	watt (W)
foot	3.048 000 x E -1	meter (m)
foot-pound-force	1.355 818	joule (J)
gallon (U.S. liquid)	3.785 412 x E -3	meter^3 (m^3)
inch	2.540 000 x E -2	meter (m)
jerk	1.000 000 x E +9	joule (J)
joule/kilogram (J/kg) radiation dose absorbed	1.000 000	Gray (Gy)
kilotons	4.183	terajoules
kip (1000 lbf)	4.448 222 x E +3	newton (N)
kip/inch^2 (ksi)	6.894 757 x E +3	kilo pascal (kPa)
ktap	1.000 000 x E +2	newton-second/m^2 ($N\text{-}s/m^2$)
micron	1.000 000 x E -6	meter (m)
mil	2.540 000 x E -5	meter (m)
mile (international)	1.609 344 x E +3	meter (m)
ounce	2.834 952 x E -2	kilogram (kg)
pound-force (lbs avoirdupois)	4.448 222	newton (N)
pound-force inch	1.129 848 x E -1	newton-meter (N-m)
pound-force/inch	1.751 268 x E +2	newton/meter (N/m)
pound-force/foot^2	4.788 026 x E -2	kilo pascal (kPa)
pound-force/inch^2 (psi)	6.894 757	kilo pascal (kPa)
pound-mass (lbm avoirdupois)	4.535 924 x E -1	kilogram (kg)
pound-mass-foot^2 (moment of inertia)	4.214 011 x E -2	kilogram-meter^2 ($kg\text{-}m^2$)
pound-mass/foot^3	1.601 846 x E +1	kilogram-meter^3 (kg/m^3)
rad (radiation dose absorbed)	1.000 000 x E -2	**Gray (Gy)
roentgen	2.579 760 x E -4	coulomb/kilogram (C/kg)
shake	1.000 000 x E -8	second (s)
slug	1.459 390 x E +1	kilogram (kg)
torr (mm Hg, 0^0 C)	1.333 22 x E -1	kilo pascal (kPa)

*The bacquerel (Bq) is the SI unit of radioactivity; 1 Bq = 1 event/s.
**The Gray (GY) is the SI unit of absorbed radiation.

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An Optical Fiber Infrasound Sensor

Introduction

A goal of current infrasound research is to devise systems to maximize the detection capability for signals of interest in the presence of ambient noise in the frequency range of a few millihertz to a few hertz. It has been well demonstrated that the principal source of noise in the requisite frequency band is turbulence in the wind field. To reduce the effects of this noise, we have designed a new type of infrasonic sensor using optical fibers as distributed sensing elements. The design addresses the limitations of the standard pipe filters currently used to average wind-generated, turbulent pressure fluctuations. In addition to maximizing the signal-to-noise ratio, the system has the capability to help estimate signal azimuth and phase velocity.

The principal advantages of the **OFIS (Optical Fiber Infrasound sensor)** over the standard pipe filter/microbarograph combination are:

1. The OFIS measures the integrated pressure variations along its length, not an acoustical sum of the pressure at many points, as is the case for the pipe filter.

2. The speed of light rather than the speed of sound governs the OFIS response. The OFIS response is thus flat across the entire infrasound frequency band. The standard pipe filter response is certainly not flat and is extremely difficult to determine in practice.

3. The OFIS can be made arbitrarily long and deployed in an arbitrary geometry. As its output is the integral of the pressure field along its length, the OFIS is inherently sensitive to signal directivity and can be deployed as a directional array element.

We have assembled a prototype optical fiber infrasound sensor, have performed laboratory evaluations, and have run comparisons of the new sensor with more traditional sensors in the field. Field experiments are conducted at the Infrasound Test Facility, part of the Cecil and Ida Green Piñon Flat Observatory. This facility includes a variety of infrasound spatial filters and recording systems, including an 8-element infrasound array composed of four 18-m and four 70-m spatial filters. This test bed has proved to be ideal for this kind of research as wind speeds vary from near zero to > 10 m/s.

We can now construct arbitrarily long lengths of the sensor. Remaining task is to investigate the best deployment geometry for optimizing the sensor as a component in an array.

Description of the Instrument

The Optical fiber Infrasound Sensor (OFIS) is constructed from a compliant, sealed tube wrapped with optical fibers to interferometrically sense deformations in the tube caused by pressure fluctuations (Figure 1). The spacing of the optical fiber wraps assures that one of the two fibers experiences greater strain than the other as the tube expands from pressure changes. Other disturbances like temperature and vibration are common to both fibers and tend to cancel.

We built a machine to wind the optical fibers onto the compliant hose with constant tension and spacing (Figures 2 and 3). One set of spools holds the tensioned optical fibers and rotates around the compliant hose as it passes through the machine, winding optical fibers onto it in a spiral. A second set of counter-rotating spools adds strips of compliant tape to hold the fibers in place.

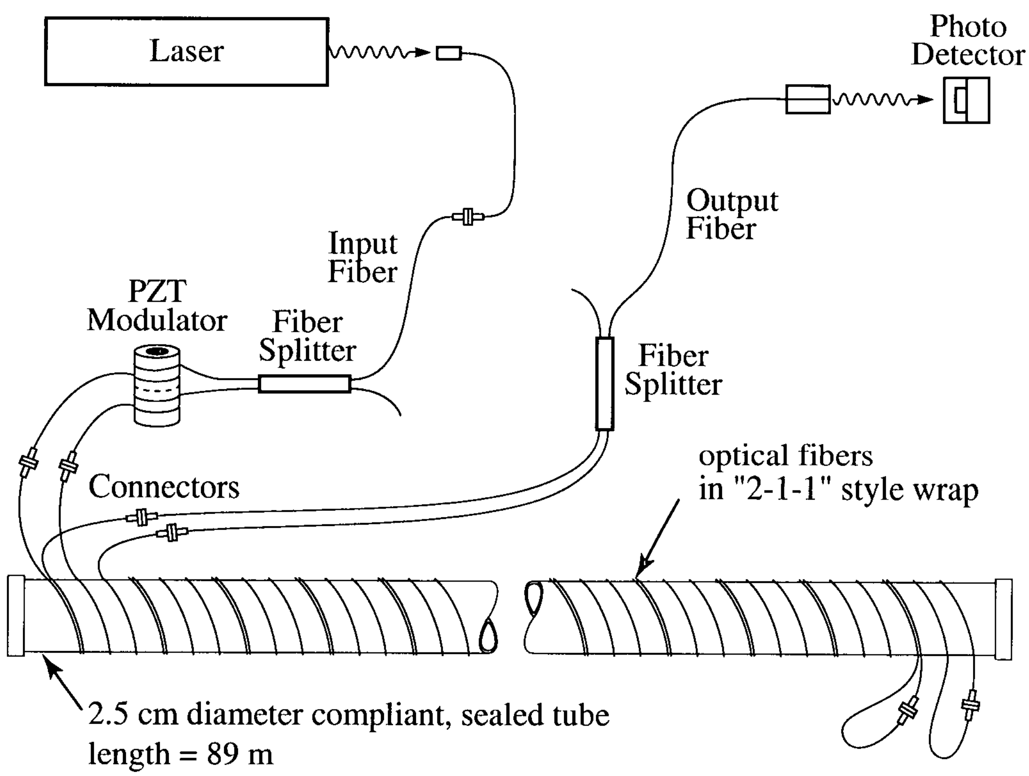

Figure 1. The Optical fiber Infrasound Sensor (OFIS).

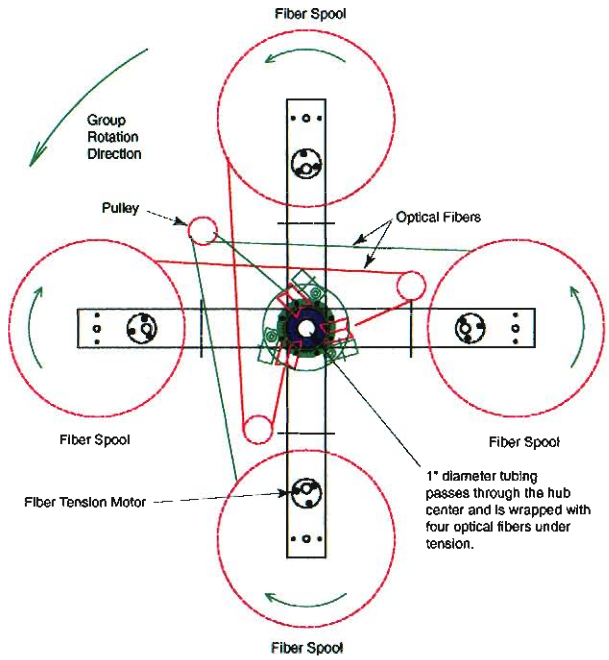

Figure 2. Schematic drawing of the winding machine

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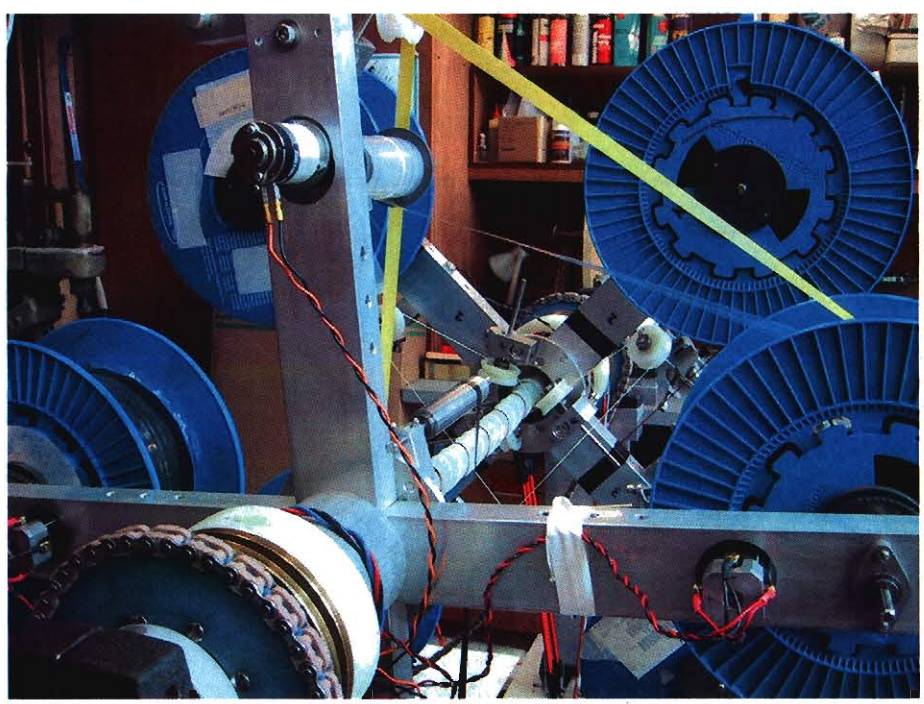

Figure 3. The OFIS winding machine.

The fibers form a Mach-Zehnder interferometer (Figure 4). A small modulation impressed onto one of the fibers is demodulated by a lock-in amplifier to produce two fringe signals in quadrature. These two signals, when plotted one against the other, form an ellipse. Expansion of the compliant tube causes the instantaneous x-y position to revolve around the ellipse ccw while contraction causes the opposite.

The quadrature fringe signals (x and y) are sampled at 200 Hz. The fringe ellipse is processed to generate a pressure signal. One lap around the ellipse (one fringe), resulting from the change in optical path through one of the fibers by one wavelength (λ = 1310 nm), corresponds to a change in pressure of 0.174 Pa (for an 89-m-long sensor). We can resolve nearly a millionth of fringe, leading to a sensor with a least-count noise of below a micropascal. As the temperature varies, the polarization of the laser drifts, causing the interferometer modulation depth to vary. Our current signal processing algorithm fits a new ellipse to each 15-minute-long data segment, then solves for the phase. Occasionally, 200 Hz is not fast enough (evidenced when the trace leaves the ellipse perimeter), and occasionally the laser hops a mode.

We have worked on a system to perform the processing in real time to yield an instantaneous pressure signal. Problems with the digitizer board we procured for this task prevented us from implementing the system, but the algorithm and interface have been completed.

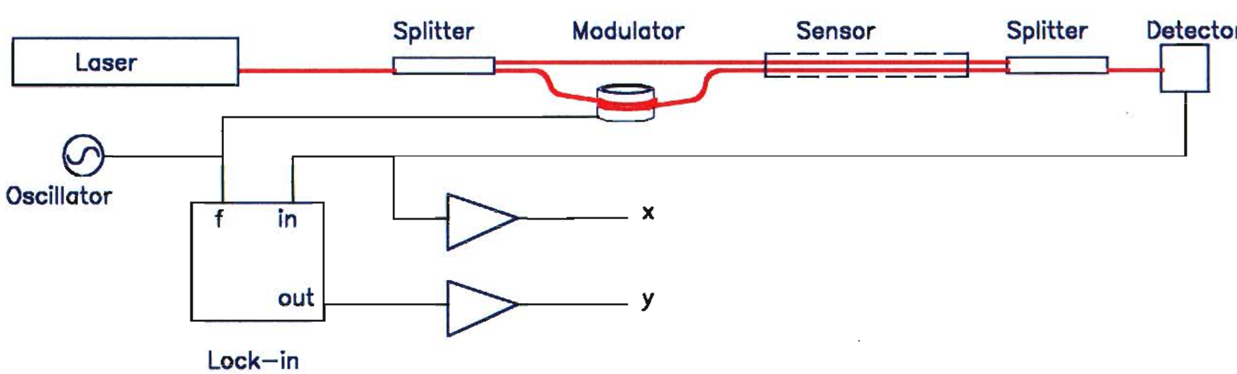

Figure 4. A schematic of the optical system.

The completed OFIS hose is wrapped in fiberglass insulation and housed in 11-cm-diameter perforated plastic drain pipe for protection (Figure 5). We installed an 89-m-long OFIS at Piñon Flat Observatory (consisting of three, 100-ft-long section) in a 40-cm-deep trench, lined with a drain pipe at the bottom (Figure 6). The OFIS was centered at 28 cm depth in the trench and covered by a layer of gravel approximately 13 cm thick. The laser and electronics were housed in a vault 40 m away and linked to the OFIS by two optical fibers and one electrical cable.

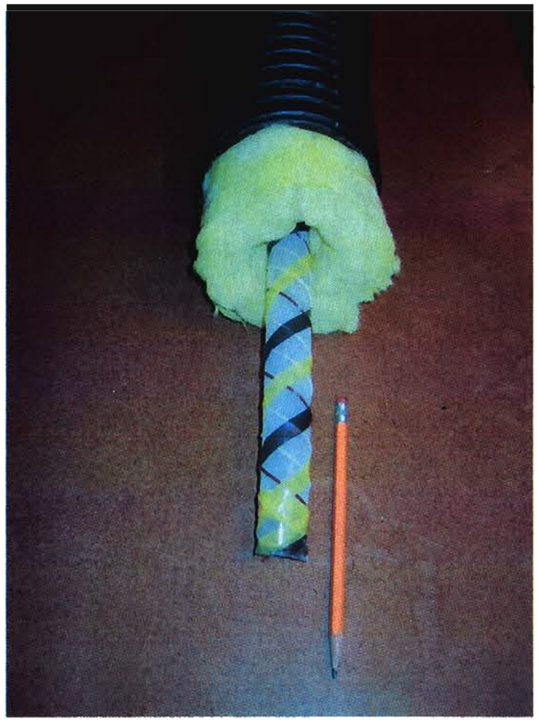

Figure 5. The OFIS hose, fiberglass insulation, and perforated plastic drain pipe.

Figure 6. The OFIS in the trench just before it was covered by a layer of gravel.

Observations and Results

We compared the OFIS records with two other infrasound sensors installed at Piñon Flat. One is a 70-m pipe array, the other is an identical pipe array but with compliant, perforated hoses connected to the ports. On September 8, 2001, an Atlas II vehicle was launched from Vandenberg AFB, 396 km from Piñon Flat. The resulting launch signal was recorded by the larger sensors at Piñon Flat. In Figure 7a we display the time series, bandpassed between 0.1 and 10 Hz, for both the 70-m-diameter pipe array (Compliant Hose Array), and the OFIS. The transfer function between OFIS and the compliant hose array was very close to 1 up to a frequency of around 3 Hz (Figure 7b).

We computed power spectra for a 15 minute time interval which includes the launch signal (Figure 8). The wind speed during this window was 1.8 m/s. The reference port (black trace) is an unfiltered MB2000. The compliant hose filter (green trace) and the L2 filter (blue trace) are both 70-m-diamter pipe arrays connected to MB2000s. The OFIS (red trace) was sampled at 200 Hz (the others are sampled at 20 Hz).

Other examples of the OFIS performance compared to the compliant hose array spectra are shown in Figure 9 for two 15 minute periods in different wind conditions. The OFIS compares favorable in low wind conditions (the 15 minute segment shown in Figure 9 is one of the quietest periods recorded by OFIS in our 4.5 day comparison experiment). Noise increases under higher wind conditions. Other sources of noise not yet identified in the OFIS are linked (we believe) to the unstabilized laser we are using.

We took 4.5 days of data from both the OFIS and the 70-m-diameter compliant-hose pipe filter (connected to an MB2000 microbarometer) and divided each into 444 fifteen-minute-long segments. Next we computed the spectrum for each of these time segments. Finally, for each frequency bin and for each instrument, we found the lowest of the 444 power levels and plotted them (the same method as used in seismology to develop the "low noise" models). In Figure 10, one can easily see the much reduced noise levels of the OFIS above about 1 Hz in comparison to the compliant hose filter. For example, at 3 Hz the OFIS noise level is some 22 dB below the level measured by the MB2000. (Note that the flattening of the spectrum of the compliant hose filter may be due to the noise of the MB2000. The manufacturer states that the "electronic noise" of the sensor is 2 mPa rms over the band between 1 and 10 Hz or 4×10^{-7} Pa^2/Hz.)

Note that among other things, these results imply that:

a. the CTBTO specification of minimum acoustic noise ("on the order of 5 mPA at 1 Hz") is quite high; and
b. the MB2000 probably cannot achieve the CTBTO requirement of noise less than 18 dB below minimum acoustic noise.

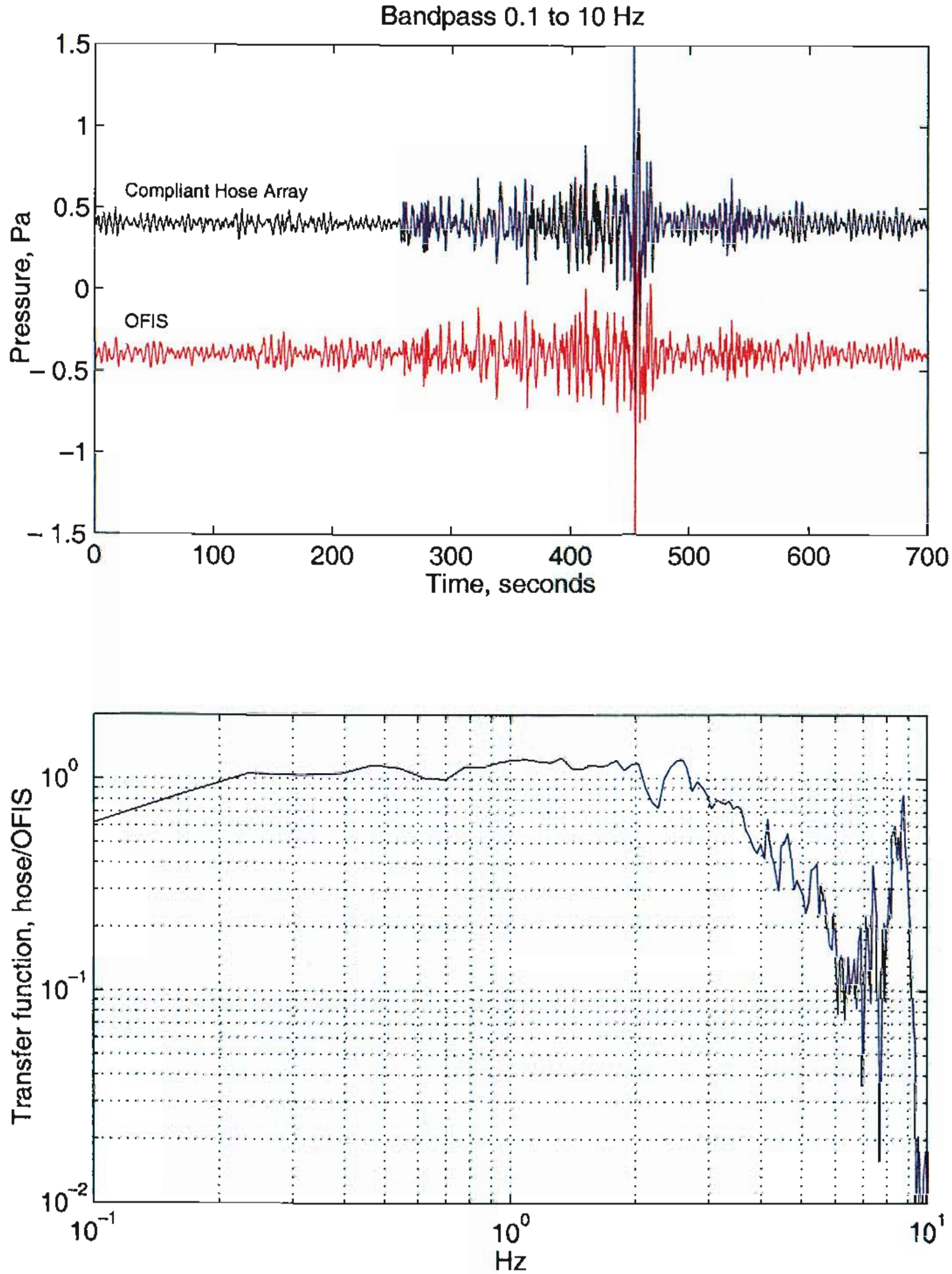

Figure 7 The top graph (a) is the time series; the bottom graph (b) is the transfer function.

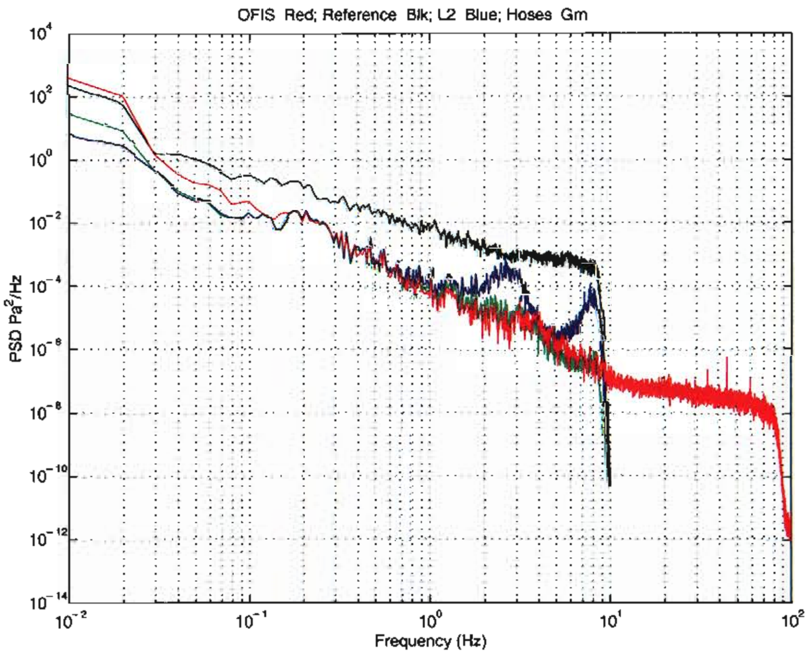

Figure 8. These are power spectra computed for a 15 minute time interval which includes the signal in Figure 12a.

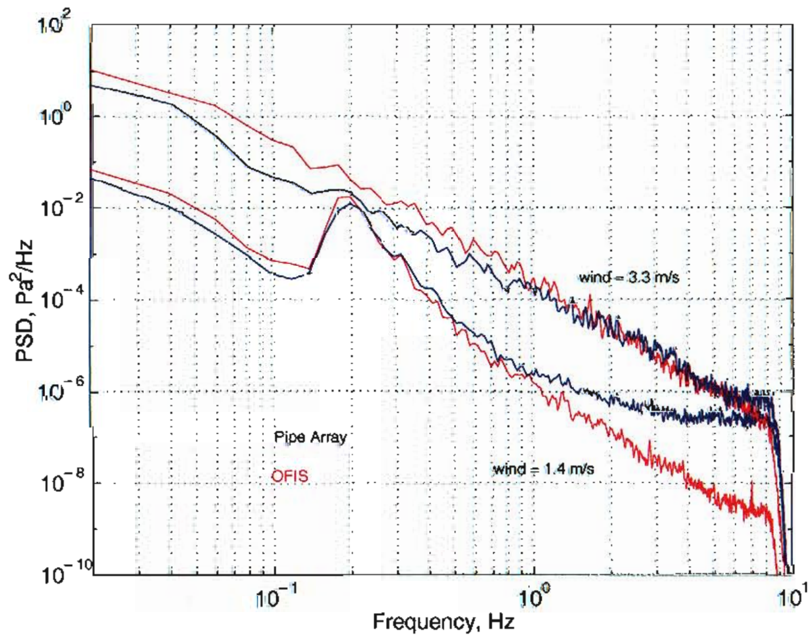

Figure 9. The OFIS (in red) and the compliant hose array spectra (in blue) for two 15 minute periods in different wind conditions.

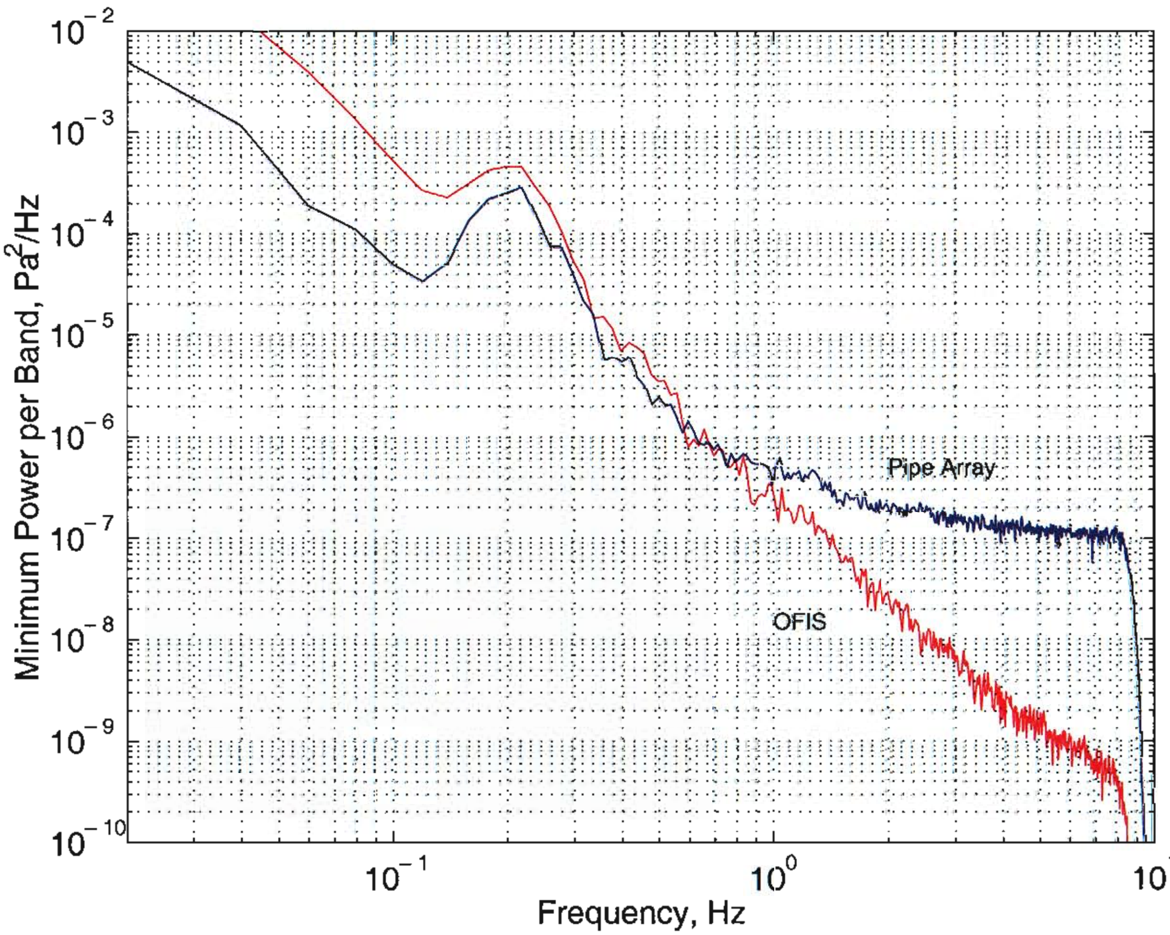

Figure 10. Minimum noise levels observed in a 4.5 day experiment.

Angular Response

An important aspect of the OFIS is that its sensitivity varies with the direction of the source—it is an infrasonic directional antenna. Consider an OFIS of length L averaging along a line in a pressure field described by

$$P(z,t) = P_0 \sin(kz - \omega t)$$

where $k = 2\pi/\lambda$ is the wavenumber of a pressure wave traveling in the z direction with velocity ω/k. If the wave vector makes an angle θ with the OFIS axis (as shown in Figure 11), then the averaging integral is

$$\overline{P}(t) = \frac{1}{L}\int_0^L P_0 \sin(kl\cos\theta - \omega t)dl$$

Computing this integral and comparing it to the pressure signal at a point, one finds an amplitude A (also relative to that at a point) of

$$A(\theta) = \frac{\sin(N\pi\cos\theta)}{N\pi\cos\theta}$$

Plotting $A(\theta)$ for various values of N yields the angular response graphs shown in Figure 12. Here we have defined the ratio of the instrument L length to the wavelength λ as $N = L/\lambda$.

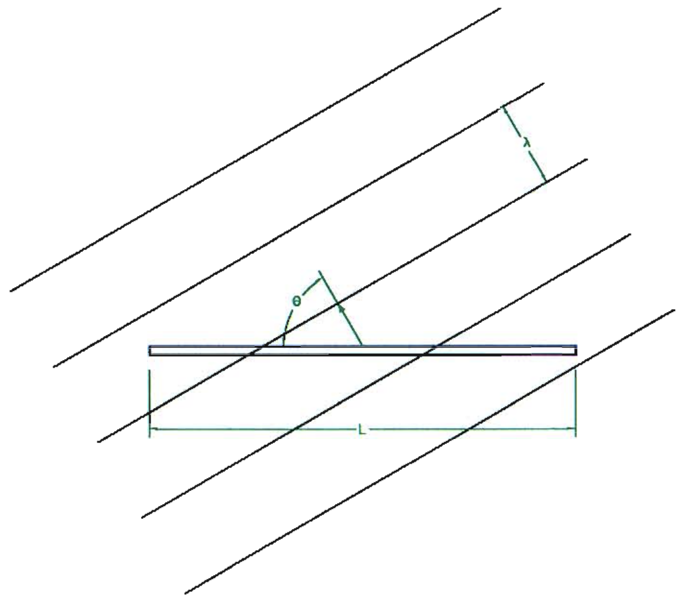

Figure 11.

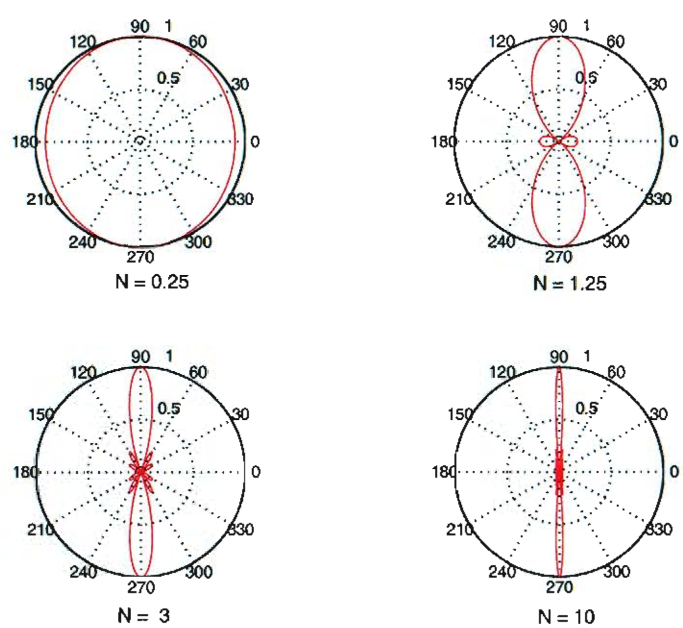

Figure 12. OFIS response as a function of arrival angle for various values of $N = L/\lambda$.

Conclusions

The OFIS is comparable to the best pipe arrays from the microbarom band up to 1 Hz. Above 1 Hz, the OFIS appears to be significantly superior than other sensors.

We have not taken advantage yet of one of the key features of the OFIS: it can be constructed arbitrarily long. In its current embodiment, it integrates the pressure field along an 89-m-long line, and we are comparing it to sensors that average the pressure over the area enclosed by a 70-m circle.

Several experiments are envisioned for furthering the development of this new tool for infrasound research:

4. We believe that a much longer sensor will yield lower noise in windy conditions because it will average away the incoherent wind-produced eddies. A 500-m-long sensor would be straightforward to construct.
5. We are operating only a single sensor. The construction of identical sensors installed at differing azimuths will allow us to study the precision with which the OFIS can determine the angle of arrival of the incident pressure waves.
6. The optical system can be improved by utilizing polarization-maintaining optical fiber and a stabilized laser.

We hope to be able to carry out some of these experiments in the near future.

Acknowledgements. We thank Michael Hedlin of UCSD, and Gene Herrin and Paul Golden of Southern Methodist University, for facilitating data collection and analysis of the compliant hose array and for providing information on the effect of gravel over our sensor. Clint Coon, Mark Gibaud, Dave Revelle, and John Unwin assisted with field deployment. Rudi Widmer-Schnidrig and Richard Hilt contributed to early lab and field tests. This research was sponsored by Defense Threat Reduction Agency under contract No. DTRA01-99-C-0056.

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